I.J. Engineering and Manufacturing, **2016, 4, 1-8**
Published Online July 2016 in MECS (http://www.mecs-press.net)
DOI: 10.5815/ijem.2016.04.01

Available online at http://www.mecs-press.net/ijem

Big Data in Cyber-Physical Systems, Digital Manufacturing and Industry 4.0

Lidong Wang[a,*], Guanghui Wang[b]

[a]*Department of Engineering Technology, Mississippi Valley State University, USA*
[b]*State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, China*

Abstract

A cyber physical system (CPS) is a complex system that integrates computation, communication, and physical processes. Digital manufacturing is a method of using computers and related technologies to control an entire production process. Industry 4.0 can make manufacturing more efficient, flexible, and sustainable through communication and intelligence; therefore, it can increase the competitiveness. Key technologies such as the Internet of Things, cloud computing, machine-to-machine (M2M) communications, 3D printing, and Big Data have great impacts on Industry 4.0. Big Data analytics is very important for cyber-physical systems (CPSs), digital manufacturing, and Industry 4.0. This paper introduces technology progresses in CPS, digital manufacturing, and Industry 4.0. Some challenges and future research topics in these areas are also presented.

Index Terms: Big Data, Big Data Analytics, Cyber-physical System (CPS), Digital Manufacturing, Industry 4.0, Cloud Computing, Internet of Things (IoT), Cybersecurity, 3D Printing, Network-based Systems.

1. Introduction

U.S. has been driving industrial Internet, cyber physical systems (CPSs), and advanced manufacturing partnership (AMP) program to advance future manufacturing. Germany is leading a transformation toward the fourth generation industrial revolution (Industry 4.0) based on the cyber-physical production system (CPPS). China has launched the 2025 Plan and Internet Plus that focus on strengthening manufacturing and accelerate service innovation [1]. On February 25, 2014, U.S. President Obama announced a $70 million award from the U.S. Department of Defense (DoD) for the Digital Manufacturing and Design Innovation (DMDI) Institute. The investment will be used to establish the Digital Lab for Manufacturing (Digital Lab) [2].

Digital Manufacturing is the use of an integrated, computer-based system that is comprised of simulation,

* Corresponding author.
E-mail address: lwang22@students.tntech.edu

three-dimensional (3D) visualization, analytics and various collaboration tools to create product and manufacturing processes simultaneously. It evolved from manufacturing initiatives such as design for manufacturability (DFM), computer-integrated manufacturing (CIM), flexible manufacturing, lean manufacturing, and others that highlight the need for more collaborative product and process design. It is the approach of using computers to control the entire production process. (http://www.plm.automation.siemens.com/en_us/plm/digital-manufacturing.shtml). Manufactures will begin to build 3D value chains (Demand oriented, Data driven, and Digitally executed). Product life-cycle management strategies will become increasingly global, multidisciplinary, innovation based, and customer focused [3].

The term Industry 4.0 has been referred to the fourth industrial revolution, or the introduction of Internet technology in the manufacturing industry to make factories more intelligent; increase ergonomics, adaptability, and resource efficiency, etc. [4]. The vision of Industry 4.0 is to go far beyond lean manufacturing or the early computer-integrated-manufacturing techniques [5]. Industry 4.0 is the vision of the industry production in the future.

Nine technologies in Industry 4.0 are transforming industrial production. The nine technologies are: simulation, augmented reality, autonomous robots, the industrial “Internet of Things”, the cloud, cybersecurity, additive manufacturing, horizontal and vertical system integration, and Big Data and analytics. The industrial Internet of Things (IoT) will link all of the company’s components, equipment, and products with embedded computing and sensors. Cybersecurity will protect manufacturers’ production lines and industrial systems from hackers and other threats [6]. Industry 4.0 and smart manufacturing support manufacturing digitally [7].

An important component of Industry 4.0 is the fusion of the physical world and the virtual world [8]. This fusion is made possible by cyber-physical systems (CPSs). Smart factories constitute a key feature of Industry 4.0. [9]. A smart factory can be defined as a factory where CPSs communicate over the IoT and help people and machines in the execution of their tasks [8]. The following is some sub-processes for a smart factory [10]:

- M2M communication via Internet of Things (IoT)
- Consistent communication from the sensor to the cloud
- Integration of robotics and innovative drive technologies
- Radio frequency identification (RFID) as the basis for parts tracking and intelligent products

The purpose of this paper is to introduce cyber physical systems (CPSs), digital manufacturing, Industry 4.0, their progresses, and Big Data analytics in the three areas. The organization of the paper is as follows: the next section introduces methods and technologies in CPSs; Section III introduces some applications digital manufacturing; Section IV introduces technologies and design principles of Industry 4.0; and the final section is conclusions.

2. Cyber-Physical Systems

Cyber means computation, communication, and control that are discrete, switched, and logical; the term physical refers to natural and human-made systems governed by the laws of physics and operated in continuous time [11]. A cyber-physical system (CPS) is defined as transformative technologies for managing interconnected systems between their computational capabilities and physical assets [12]. A CPS is a system of collaborating IT elements and being designed to control physical (mechanical, electronic) objects. Communication takes place via a data infrastructure such as the Internet. Traditional embedded systems can be regarded as a special case of a stand-alone CPS [13].

A CPS generally consists of two main functional components: (a) the advanced connectivity that ensures real-time data acquisition from the physical world and information feedback from the cyber space; (b) intelligent data management, computational and analytics capability that constructs the cyber space [12]. Some technologies that are closely connected to the CPS are IoT, wireless sensor networks, and cloud computing. Wireless sensor networks are regarded to be a vital component of CPS [14]. The Internet technology provides essential approaches to enhancing the performance of cyber-physical systems. Internet technology approaches comprise the following concepts [15]:

- The Internet of Things (IoT): It comprises communicating smart systems using IP addresses. This enables each physical object being equipped with a unique IP address.
- The Internet of Services (IoS): It comprises new service paradigms such as being provided by the service oriented architecture (SOA) or the REST-technology.
- The Internet of Data (IoD): It enables to store and transfer mass data appropriately, and to provide new and innovative analysis methods for interpreting mass data.

A 5-level CPS structure has been proposed. It defines how people construct a CPS from the initial data acquisition, then analytics, and to the final value creation. It is outlined in Table 1 [16]. Among the $5C$ levels, the cognition and configuration levels are the most difficult to achieve [17].

Table 1. $5C$ Architecture for the Implementation of a Cyber-physical System

Levels	**Descriptions**
Smart *Connection*	Acquiring accurate and reliable data from machines and their components is the first step
Data-to-information *Conversion*	Meaningful information has to be inferred from data.
Cyber	This level acts as a central information hub in this architecture. Having massive information gathered, specific analytics have to be conducted to extract additional information for providing better insight.
Cognition	Implementing CPS upon this level generates a thorough knowledge of the monitored system. A proper presentation of the acquired knowledge to expert users supports a correct decision.
Configuration	This level is the feedback from the cyber space to the physical space and acts as a supervisory control to make machines self-configure and self-adaptive. This stage acts as a resilience control system (RCS) to apply corrective and preventive decisions.

Cyber physical systems (CPSs) in a manufacturing and automation context can be referred to different manufacturing processes including simulation, design, control, and verification. Emerging CPSs will be connected, distributed, and coordinated; they must be responsive and robust. In manufacturing, CPSs can improve quality and productivity through smart prognostics and diagnostics using big data from different machines, networked sensors, and systems [17]. In manufacturing, a CPS can combine progresses, which is achieved by large computing systems on planning, modelling, and prediction with the power of data that is generated during manufacturing processes by a lot of small data-driven devices such as actuators, sensors, or RFID readers. These devices are enabled by advances in cognitive control systems and M2M communications. A CPS in manufacturing is also called cyber-physical production system (CPPS) [30]. Sometimes, it is necessary to perform a real-time processing of massive amount of high-dimensional data with low quality or low information content collected by CPS sensors. Online processing of high dimensional and low-quality data is a challenge [18]. For more complicated manufacturing systems, for example, semiconductor manufacturing, the integration of data from heterogeneous sources (different suppliers, different time stamps, and different data formats) is also a challenge [17].

For the security of cyber-physical systems, advanced technologies are needed to provide a secure infrastructure for managing information assets in a manufacturing environment. In addition to known vulnerabilities in manufacturing, it is needed to handle new vulnerabilities of cyber physical systems in intelligent machines with sensors and control systems [19]. A CPS can be further developed for managing big data and leveraging the interconnectivity of machines to reach the goal of resilient, intelligent, and self-adaptable machines [12]. The role of Big Data analytics for cyber-physical production systems (CPPS) will reach into design, manufacturing, maintenance, use, and reuse when people try to handle new types of data and problems [4].

3. Digital Manufacturing

Digital manufacturing is the methodology that uses an integrated and computer-based system to create product and manufacturing process definitions simultaneously. The computer-based system consists of analytics, simulation, three-dimensional (3D) visualization, and various collaboration approaches and tools (http://www.plm.automation.siemens.com/en_us/plm/digital-manufacturing.shtml). Therefore, there is difference between the term digital manufacturing and the term smart manufacturing with smart control and automation, Digital thread is often associated with digital manufacturing. It refers to the integrated chain of data from conception, manufacture, and to end product. This means that modeling processes are focused on design, prototyping, and the use of computer-aided process planning (CAPP), computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided engineering manufacturing (CAM) technologies that facilitate digital threads [20].

The U.S. government announced in 2014 that $70 million would be invested to create the Digital Laboratory for Digital Manufacturing and Design Innovation (DMDI). DMDI identifies high-performance computing (HPC) and advanced analytics as a key enabler. The Digital Laboratory has planned to use cutting-edge technologies such as mobile technology, cloud computing, and HPC technologies in manufacturing. This will also create online networks of manufacturing machines, factories, and people. In turn, it will help enable real-time collaboration and analysis of big data during design and manufacturing processes [2].

Digital manufacturing progresses very fast. Robotics and CAD/CAE/CAM/CAPP are conventional supporting technologies for digital manufacturing. In addition, Internet of Things (IoT), additive manufacturing (commonly called 3D printing), and Big Data analytics, etc. are emerging technologies in digital manufacturing. Technology advances and growth in all these areas are rapidly changing the industry. For example, IoT lays a solid foundation for digital technologies to transform manufacturing [21]. Big Data analytics will improve manufacturing efficiency by improving equipment service, reducing energy costs, and improving production quality. By collecting and analyzing data from different sources such as equipment and customer management systems, managers can make better decisions in time [6].

Digital manufacturing can also enable customization. For example, 3D printing allows products to be manufactured on-demand from electronically communicated digital designs. It is easy to modify or update digital information in manufacturing according customers' requirements [22]. 3D printing includes several technologies that are based on different physical mechanisms. The common feature is the generation of 3D physical objects from digital models [21]. Industry4.0 is the comprehensive transformation of the whole sphere of industrial production through the merging of technologies such as digital technology and the Internet with conventional industry [23]. Industry 4.0 is a combination of many elements such as massive data, analytics, cloud computing, network security, and distributed intelligence, etc. Such elements are important to the "Digital Factory", which improves manufacturing efficiency and productivity [24].

4. Industry 4.0

Industry 4.0, the fourth industrial revolution, is triggered by digital technologies that have significant influence on manufacturing. A variety of concepts and solution-components were drawn and studied to fulfill the vision of Industry 4.0. These include, but is not limited to (1) CPSs as intelligent entities in production or manufacturing [25], (2) Internet of Things (IoT) as communication platform for CPSs, (3) Cloud solutions for decentralized services [26], and (4) Big Data solutions for high-performance processing of big data with large amounts in volume, variety, speed, variability, or veracity, etc. in manufacturing [9] [27]. With regard to Industry 4.0, the mobile Internet is very important for a connected manufacturing environment. For example, object tagging and Internet-to-object communication is vital for real-time data capturing and accessibility. Cloud computing can offer computing and storage power for digitally enhanced production or manufacturing.

M2M can be regarded as the integral technology of IoT. M2M communication allows for the automatic information exchange between CPSs that constitute the Industry 4.0 production environment [28].

The Industrial Internet, sometimes also referred to as the Industrial Internet of Things (IIoT), draws together fields such as M2M communication, machine learning, and Big Data analytics to collect data from machines, analyze it, and use it to adjust operations. Visual computing is an important technology in the Industry 4.0 and IIoT initiatives to design and fulfill smart and cognitive behavior in manufacturing [4]. A key approach of Industry 4.0 is to equip future products and production systems with embedded systems as a basis for smart sensor and smart actuators that enable communication and intelligent operation control. Industry4.0 uses the ability of cyber-physical systems to provide communication and intelligence for smart systems [15]. Industry 4.0 can offer the following advantages [29]:

- More flexibility: Networks enable business processes to be structured more dynamically. Production procedures react more flexibly to changes in demand.
- Reduce lead times: Seamless data collection allows the rapid use of production-relevant data and information for near-term decision-making, and therefore reduces lead times for innovations in the market.
- Adapting to customer demands with small batch sizes: Industry 4.0 enables the incorporation of individual customer-specific criteria concerning planning, configuration, ordering, design, production, and operation. It also allows modifications in time.
- New offerings of downstream services: Industry 4.0 has the potential for high-performance services for the near-term evaluation of big data.

Industry 4.0 mainly depends on several innovative technologies and they are listed as follows [23]:

- Modelling, simulation, and virtualization in design and manufacturing.
- Information and communication technology (ICT) to digitize information and integrate various systems at all stages of product development and use.
- Network communications including wireless and Internet technologies that link machines, systems, work products, and people.
- Greater ICT-based support for human workers, including robots, intelligent tools, and augmented reality.
- Cyber-physical systems that use ICTs to monitor and control physical processes and systems. Embedded sensors and intelligent robots may be used.
- Collection of large quantities of data, their analysis, and exploitation through cloud computing and Big Data analytics.

Six design principles [8] for implementing Industry 4.0 are described in Table 2.

Table 2. Six Design Principles for Industry 4.0

Principles	**Descriptions**
Interoperability	CPSs and humans are connected over the IoT and the IoS. All CPSs within a plant are able to communicate with each other "through open nets and semantic descriptions".
Virtualization	Sensor data are linked to simulation models and virtual plant models, creating a virtual copy of the physical world. CPSs are able to monitor physical processes.
Decentralization	Plant decentralization means that devices like RFID tags "tell" machines what working steps are necessary. Embedded computers enable CPSs to make decisions on their own.
Real-time capability	Real-time data collection and analysis should be performed so that a plant can react to the failure of a machine in time and reroute a work-in-process or products to another machine.
Service orientation	The services of CPSs, humans, and companies are available over the IoS. All CPSs offer their functionalities as an encapsulated web service.
Modularity	Modular systems enable flexible adaption to changing demands by expanding or replacing individual modules.

Six design principles can be derived from some Industry 4.0 components, which is listed in Table 3 [8].

Table 3. Design Principles of Some Industry 4.0 Components

	Cyber-Physical Systems	**Internet of Things (IoT)**	**Internet of Services (IoS)**	**Smart Factory**
Interoperability	X	X	X	X
Virtualization	X	-	-	X
Decentralization	X	-	-	X
Real-time capability	-	-	-	X
Service orientation	-	-	X	-
Modularity	-	-	X	-

In Industry 4.0, companies can be integrated both horizontally and vertically so that data and information can be exchanged within the companies and beyond their walls [6]. While the implementation of Industry 4.0, companies should deal with the following factors [24]:

- Cloud Computing: It enables the processing of huge amount of data, and allows extensive simulations of different aspects in industrial operation.
- Global Database: Industry 4.0 relies on data/information sharing among logistics and production centers of companies.
- Automation: Automation systems based on Industry 4.0 link the physical world and the virtual information (often digital) environment by integrating information processing units with sensors/actuators.
- Networks: Industry 4.0 standards use TCP/IP, the most common Internet protocol, to link a lot of devices.

5. Conclusions and Future Work

A cyber-physical system (CPS) is the convergence of information, computation, communication, and control. Digital manufacturing can improve productivity in production processes as well as manufacturing planning. Four fundamental conceptual approaches of Industry 4.0 are: CPSs, Internet technology, components as information carriers, and holistic safety and security including privacy and knowledge protection. Big Data, CPSs, mobile computing, cloud computing, and Internet of the Things (IoT), etc. have great impacts on Industry 4.0. Cybersecurity in manufacturing, Big Data Analytics for heterogeneous data in manufacturing, and Big Data Analytics in real-time processing of sensor data or stream data generated in the manufacturing environment are important future research topics.

Acknowledgements

The authors are very much thankful to the reviewers for their comments and suggestions to improve the quality of the manuscript.

References

[1] J. Lee (2015). Recent Advances of Predictive Big Data Analytics and Industry 4.0 for Future Manufacturing and Service Innovation. Technical Report, University of Cincinnati, USA.

[2] A. Isakson, T. Peters, J. Harris, M. Malone (2014). U.S. Department of Defense Awards $70 Million Grant to UI LABS-led Team. White Paper, UILAB, Chicago, IL, USA.

[3] S. Mitra (2015). Digital Manufacturing POV. Technical Report, Hewlett-Packard Development Company, Feb 12.

[4] A. Stork (2015). Visual Computing Challenges of Advanced Manufacturing and Industrie 4.0. *IEEE Computer Graphics and Applications*, March/April, 21-25.

[5] M. Anne, M. Gobble (2014). News and Analysis of the Global Innovation Scene. *Research Technology Management*, November/December, 2-3.

[6] Audio-Tech Business Book Summaries, Inc. (2015). Industry 4.0 and the U.S. Manufacturing Renaissance. *Trends E-Magazine*, June, 4-10.

[7] S. Schabus and J. Scholz (2015). Geographic Information Science and Technology as Key Approach to Unveil the Potential of Industry 4.0. *ICINCO 2015 - 12th International Conference on Informatics in Control, Automation and Robotics*, 463-470.

[8] M. Hermann, T. Pentek, B. Otto (2015). Design Principles for Industrie 4.0 Scenarios: A Literature Review. Working Paper, TU Dortmund University, Germany, No. 1.

[9] H. Kagermann, W. Wahlster, and J. Helbig (2013). Recommendations for implementing the strategic initiative Industrie 4.0. Final Report of the Industrie 4.0 Working Group, National Academy of Science and Engineering, Germany, April.

[10] Beckhoff Automation GmbH (2013). PC-based Control – The technological foundation for Industrie 4.0. Technical Report, November.

[11] T. Nadeem (2013). Cyber Physical Systems Seminar, Dept. of Computer Science, Old Dominion University, USA, Spring.

[12] J. Lee, B. Bagheri, H.-A. Kao (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters 3*, 18–23.

[13] F. Schoenthaler, D. Augenstein, T. Karle (2015). Design and Governance of Collaborative Business Processes in Industry 4.0. *Proceedings of the Workshop on Cross-organizational and Cross-company BPM (XOC-BPM)* co-located with the *17th IEEE Conference on Business Informatics (CBI 2015),* Lisbon, Portugal, July 13, 1-8.

[14] A. Kos, S. Toma, J. Salom, N. Trifunovic, M. Valero, and V. Milutinovic (2015). New Benchmarking Methodology and Programming Model for Big Data Processing. *International Journal of Distributed Sensor Networks*, Article ID 271752, 1-7. http://dx.doi.org/10.1155/2015/271752

[15] I. R. Anderl (2014). Industrie 4.0 - Advanced Engineering of Smart Products and Smart Production, Technological Innovations in the Product Development. *19th International Seminar on High Technology*, Piracicaba, Brasil, October 9th, 2014, 1-14.

[16] J. Lee, H. D. Ardakani, S. Yang, B. Bagheri (2015). Industrial big data analytics and cyber-physical systems for future maintenance & service innovation. *The Fourth International Conference on Through-life Engineering Services, Procedia CIRP*, 38, 3-7.

[17] H.-A. Kao, W. Jin, D. Siegel and J. Lee (2015). A Cyber Physical Interface for Automation Systems-Methodology and Examples. *Machines*, 3, 93-106, doi: 10.3390/machines3020093.

[18] T. Hunter, T. Das, M. Zaharia, P. Addeel, A. M. Bayen (2012). Large Scale Estimation in Cyber-physical Systems Using Streaming Data: a Case Study with Smartphone, Traces. arXiv.org, 1212.3393v1.

[19] http://www.manufacturing.gov/docs/DMDI_overview.pdf

[20] https://smartmanufacturingcoalition.org/sites/default/files/nst-smlc-workshopbackground.pdf

[21] IBM Corporation (2015). The digital overhaul: Rethinking manufacturing in the digital age, Technical Report, May.

[22] http://energy.gov/sites/prod/files/2015/02/f19/QTR%20Ch8%20-%20Smart%20%20 Manufacturing%20 TA%20Feb-13-2015.pdf

[23] R. Davies (2015). Industry 4.0 Digitalization for productivity and growth," *European Parliamentary Research Service (EPRS)*, Briefing, 1-10.

[24] I. Singh, N. Al-Mutawaly, and T. Wanyama (2015). Teaching network technologies that support Industry 4.0. *Proc. 2015 Canadian Engineering Education Association (CEEA15) Conf*., CEEA15; Paper 119, McMaster University; May 31-June 3, 1-5.
[25] J. Sztipanovits, S. Ying, D. Corman, J. Davis, P. J. Mosterman, V. Prasad, and L. Stormo (2013). Strategic R&D Opportunities for 21st Century Cyber-Physical Systems Workshop Report: Foundations for Innovation in Cyber-Physical Systems, National Institute of Standards and Technology (NIST), January. http://events.energetics.com/NIST-CPSWorkshop/downloads.html
[26] A. Verl, A. Lechler, S. Wesner, A. Kirstädter, J. Schlechtendahl, L. Schubert and S. Meier (2013). An Approach for a Cloud-based Machine Tool Control. *CIRP Conference on Manufacturing Systems*, Elsevier B.V., 7, 682–687.
[27] J. Lee, E. Lapira, B. Bagheri, and H. Kao (2013). Recent advances and trends in predictive manufacturing systems in big data environment. *Manufacturing Letters*, Society of Manufacturing Engineers (SME), *1*(1), 38–41.
[28] J. Bechtold, C. Lauenstein, A. Kern, L. Bernhofer (2014). Industry 4.0 - The Capgemini Consulting View. Technical Report, Capgemini Consulting.
[29] S. Heng (2014). Industry 4.0 Upgrading of Germany's industrial capabilities on the horizon. *Deutsche Bank Research*, Germany, April 23.
[30] E. Legziel, M. Wollschlaeger, P. Fantini, V. Vasyutynskyy (2013). Cyber-physical systems in manufacturing and production. Workshop Report, PLANTCockpit, Italy, December 13.

Authors' Profiles

Dr. Lidong Wang is an Associate Professor in the Department of Engineering Technology at Mississippi Valley State University, USA. He worked at Ohio State University, Mississippi State University, and the University of South Carolina; and conducted projects supported by the Department of Defense (DOD), the National Science Foundation (NSF), and the National Aeronautics and Space Administration (NASA). His current research interests include Big Data, cloud computing, cyber-physical systems, digital manufacturing, and Industry 4.0, etc. He has published over 70 papers in various journals. He was the President of the Electricity, Electronics & Computer Technology (EECT) Division of the Association of Technology, Management, and Applied Engineering in USA. He was the Editor-in-Chief of the International Journal of Automated Identification Technology (IJAIT) from 2008 to 2015. He has also been invited by four professional journals to act as their guest editor.

Dr. Guanghui Wang is a professor at the State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, China. He worked as a research scholar at the University of Vermont in USA, York University in Canada, and the University of Western Australia in Australia. His current research areas include computational mathematics, Big Data analytics, computer applications, cyber-physical systems, and numerical analysis and weather prediction, etc. He has published over 50 papers in academic journals.

How to cite this paper: Lidong Wang, Guanghui Wang ,"Big Data in Cyber-Physical Systems, Digital Manufacturing and Industry 4.0", International Journal of Engineering and Manufacturing(IJEM), Vol.6, No.4, pp.1-8, 2016.DOI: 10.5815/ijem.2016.04.01